AUTOMATED DAMAGE ASSESSMENT SYSTEM FOR BALLISTIC PROTECTIVE INSERTS USING LOW FREQUENCY ULTRASONICS

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ABSTRACT

Ballistic Protective Inserts (BPI) provide personal ballistic protection through several layers of materials such as ceramic plates and composite fibers. The complex BPI structure makes inspection with conventional nondestructive testing methods difficult. Radiography and low frequency ultrasonics are two methods that can provide information about the condition of a BPI, with respect to cracking and porosity in the ceramic plate and debonding between layers. Although both ultrasonics and radiography are sensitive to the presence of cracking and porosity, ultrasonics may be more sensitive to the presence of debonds, which makes it a powerful tool for BPI evaluation. In this paper, we discuss the development and application of an automated inspection system, which uses low frequency ultrasonics and a newly developed mathematical algorithm to assess the condition of BPI.

1. INTRODUCTION

Primary ballistic protection offered against small arms rounds is commonly based on a structure that uses a ceramic tile with a composite backing. The mechanism of protection lies in the absorption and dissipation of the projectile's kinetic energy by the local shattering of the ceramic tile and blunting the bullet material on the hard ceramic. The composite backing material then spreads the energy of the impact to a larger area and stops the fragments, preventing injury to the soldier.

BPI containing ceramics can be susceptible to low velocity impact damage, which can produce cracking in the ceramic plate or separation between the ceramic and the composite backing plates. Low velocity impact can be produced by accidentally dropping the BPI onto a hard surface during transportation and storage, or by the impact caused by a user wearing a BPI landing on uneven hard surfaces. Thus, there is a need for the development of a NDE technology which can address these complicated assessment issues.

Physical Acoustics Corporation (PAC) has developed and tested a prototype Ballistic Protective Inserts Condition Assessment System (BPICAS). This system was developed under the Small Business Innovative Research (SBIR) Program *"In-Service Technique for Assessing Conditions of Ballistic Protective Inserts in Personnel Armor"* awarded to PAC by the U.S. Army Natick Soldier Center. Phase I of the project was successfully completed in August 2002. Phase I Option started in September 2003 and was completed in December 2003. The final Phase of the project, Phase II, started in January 2004 and was successfully completed in January 2006. In this paper, we discuss the development of the inspection system, the algorithms used in the evaluation of the BPI and the correlation obtained between BPICAS results and ballistic performance.

2. DESCRIPTION OF THE INSPECTION SYSTEM

2.1. Overall System Description and Operation

The BPICAS, shown in Figure 1, which allows for the inspection of BPI in the field, consists of a modular, yet portable, aluminum frame with a conveyor belt, a variable speed motor, and two sets of acoustic sensors, that act as pulsers and receivers. The operation of the BPICAS is completely automatic and only requires the operator to position the BPI on the conveyor belt, enter a file name and push a button. The system automatically moves the BPI through the different steps in the inspection process which result in a number that is then used to assess the condition of the BPI.

The four rolling sensors placed below the conveyor belt (BPI backside) send acoustic waves through the cross section of the BPI that are detected by the five rolling sensors located above the conveyor belt (BPI front side) as shown in Figure 2. The pulsing sensors, placed at 2" intervals along the width of the BPI, are excited sequentially, and the signals detected by the five receivers, also placed at 2" intervals, are recorded. This process is repeated at 0.125" intervals along the length of the BPI until the target BPI area is completely inspected. The

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detected waveforms are analyzed using a mathematical algorithm that evaluates the overall condition of the BPI and classifies it as Pass/Fail. The current inspection time of a BPI is about two minutes.

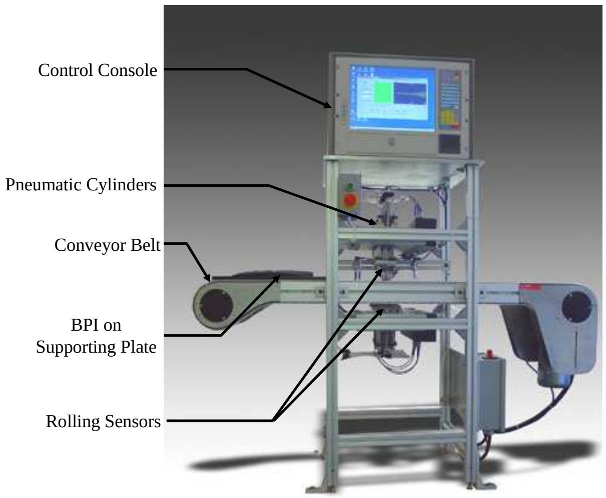

Fig. 1 BPI Condition Assessment System (BPICAS).

The BPICAS evaluation algorithm is based on searching for a certain pattern in the acoustic waves propagating through the thickness of a BPI. The acoustic waves interact with discontinuities (cracks, debonds, porosity) present in the different components of the BPI and their characteristics change depending on the extent of these discontinuities. It is possible to determine the overall condition of the BPI by monitoring the pattern changes and compare them with acoustic waves propagating through BPI with no discontinuities (damage).

2.2. Data Processing and Analysis

The inspection method is based on low frequency acoustic waves propagating through the BPI cross section. Pulsers generate chirp signals in the frequency range of 100-250kHz which provides the best combination of sensitivity and penetration through the complex BPI structure. For each inspection line, a total of 20 waveforms are recorded by the receivers. However, due to the complicated paths along which the waves propagate inside the BPI, and the strong attenuation produced by different interfaces, only the waveforms produced by the two adjacent pulsers to each receiver (as shown in yellow lines in Figure 2) are used in the damage assessment.

The baseline data recorded from undamaged BPI show that the waveforms have similar profiles and similar arrival times; however they exhibit varying signal amplitudes from one line to the next for the same receiving sensor. Difference is also observed from one receiving sensor to another for the same scan line. The

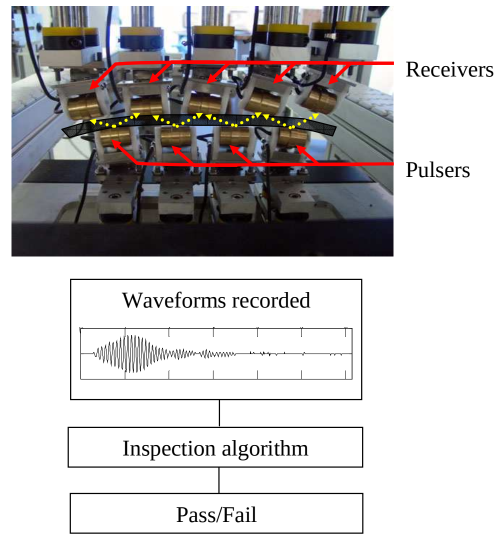

Fig. 2 Sensor locations and principal steps for evaluation of sensor output waveforms.

potential sources of amplitude changes are the coupling variations of the pulsing and receiving sensors and the non-conformity of the BPI cross section. Figure 3 shows examples of waveforms recorded from ten consecutive scan lines of an undamaged BPI specimen for the same receiver. The waveforms exhibit a repeating signature having a 150kHz dominant frequency and varying amplitude values.

Baseline data recorded from BPI with damage induced by controlled low velocity impact show that the waveforms have different signatures as compared to those obtained from undamaged BPI. The signals disperse to

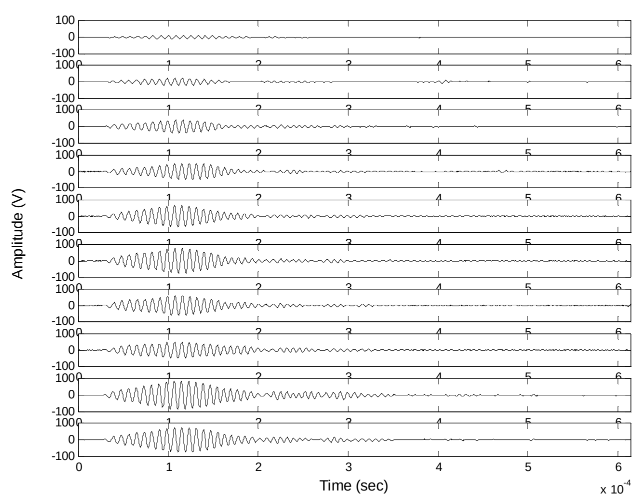

Fig. 3 Waveforms detected on an undamaged BPI by a receiver for ten consecutive scan lines.

the lower frequencies at the damaged locations. As an example, Figure 4 shows waveforms recorded from a damaged BPI by a receiver for ten consecutive scan lines.

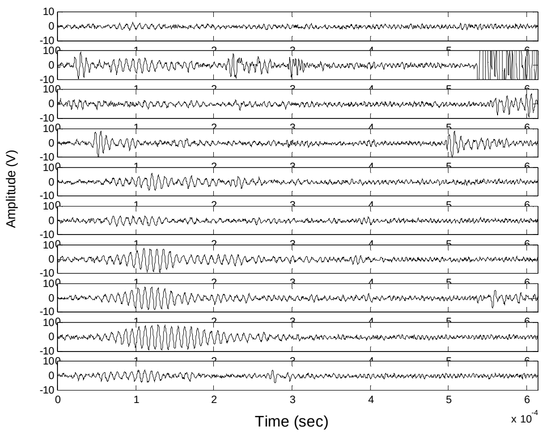

Fig. 4 Waveforms detected on a damaged BPI by a receiver for ten consecutive scan lines.

2.3. Algorithm to Assess the Overall Damage of the BPI

As discussed above, the waveform profiles recorded from the undamaged and damaged BPI show changes that relate to the condition of the BPI. By evaluating these changes, the BPI condition can be assessed and a single number correlated to the ballistic performance of the BPI can be generated.

In order to generate a condition "number", a mathematical algorithm was developed. The basic idea behind the algorithm is as follows: if there is no damage in the signal path between a pulser and a receiver, the waveform should have a profile similar to those shown in Figure 3. If there is any discontinuity in the signal path, the waveform profile would change as shown in Figure 4.

The best way to evaluate the difference between two waveforms is the cross correlation method. The cross correlation function for discrete and finite duration signals is

$$R_{y_1y_2}(\tau) = \sum_{t=1}^{N} y_1(t)\,y_2(t+\tau) \qquad (1)$$

where $R_{y_1y_2}(\tau)$ is the cross correlation coefficient of two signals, y_1 and y_2, as a function of time delay τ, N is the length of signals. In signal processing, the cross correlation function reveals the degree of similarity between two signals as a function of time delay. A distinct peak means that two signals are matched for that particular time delay.

Figure 5 shows the flow of the algorithm used in BPI condition assessment. After a BPI specimen is tested using the BPICAS, the relevant waveforms detected by the receiving sensors for each scan are selected. When the waveforms are cross correlated to a reference waveform that has an expected profile, the time delay between the waveforms and the reference should be less than the assigned threshold to classify them as good waveforms. The time delay threshold value was determined by the statistical analysis derived from the testing of a large sample of damaged and undamaged BPI.

If the time lag is greater than the time lag threshold, the program begins counting waveforms. If the number of waveforms per BPI specimen (count #) that exceed the threshold time lag is less than the Pass/Fail threshold determined by ballistic tests, the BPI specimen passes the test, otherwise it fails.

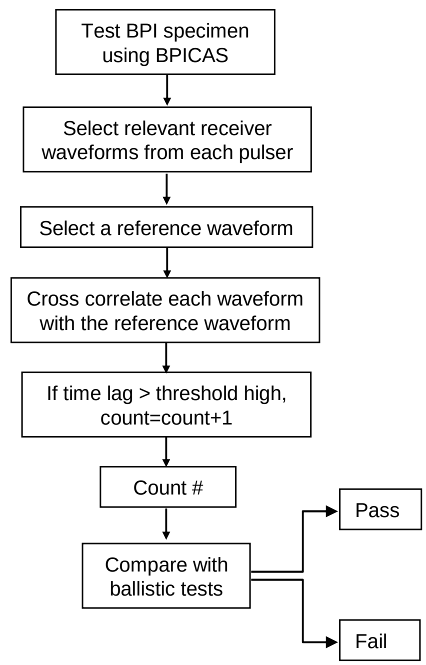

Fig. 5 Flow chart of the algorithm for BPI condition assessment.

3. PERFORMANCE EVALUATION

For BPICAS performance evaluation, two sets of BPI samples were tested: one set containing both damaged and undamaged BPI and a second set of undamaged BPI recently manufactured. The first set was used to establish the Pass/Fail threshold using the ballistic performance test results; the second set was used to test this threshold.

3.1. Sample Set 1

Natick Soldier Center provided a set of twenty nine large-size BPI for evaluation with the BPICAS. These BPI included both damaged and undamaged samples as confirmed via X-ray inspection. The twenty nine BPI were tested using the BPICAS inspection system. Each BPI was tested five times and the average value was associated to the corresponding BPI. Figure 6 shows the inspection results together with ballistic performance

results. The distribution of test results is categorized into four regions: “True Positives”, “True Negatives”, “False Negatives” and “False Positives”. The BPICAS Pass/Fail threshold was set at such a level that there would not be any sample grouped in the area of “False Positives”. “True Positives” are the BPI identified as “Pass” by the BPICAS and passed in the ballistic test. “True Negatives” are the BPI identified as “Fail” by the BPICAS and failed in the ballistic test. Ideally, all the tested BPI are expected to be ranked in these regions which agree with the ballistic performance. “False Positives” represent undetected damage and any BPI classified in this region reduces the reliability of the inspection method. No BPI were classified as “False Positives”.

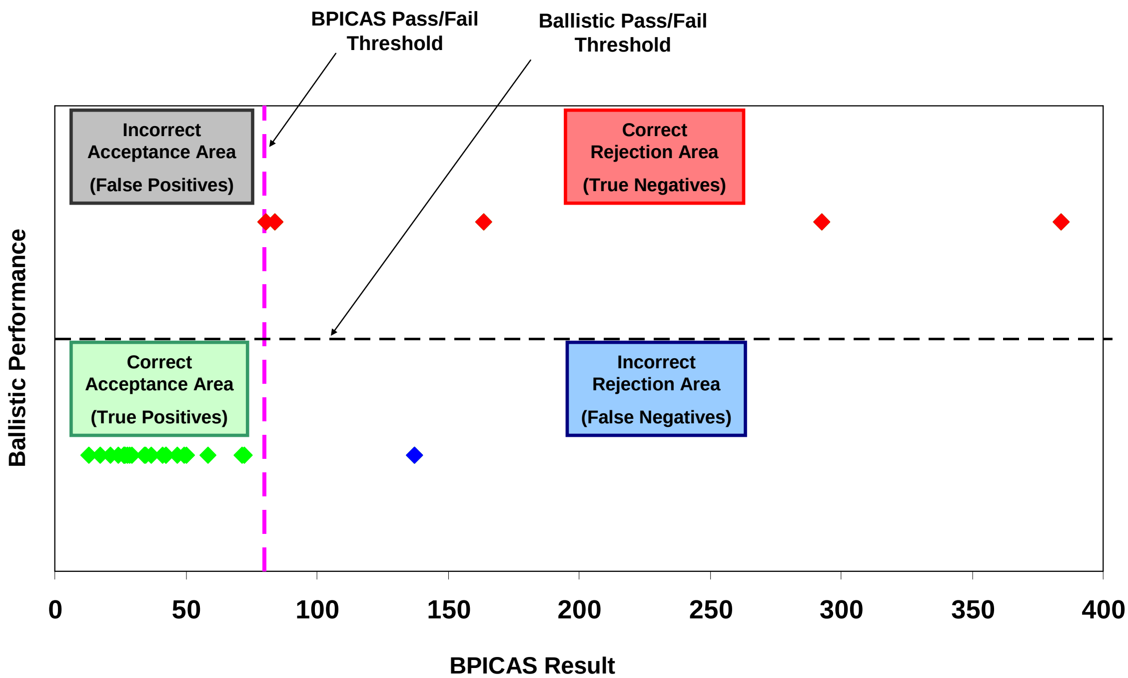

Fig. 6 BPICAS and ballistic test results of the BPI set retrieved from the field and distribution areas for correct and incorrect Pass/Fail decisions

As shown in Figure 6, there is one BPI in the region of “False Negatives” which means that the BPICAS failed the BPI but the ballistic test passed it. Further analysis of the X-Ray result of this BPI indicates that the BPI was damaged. This is an indication that a ballistic test may pass a damaged BPI while BPICAS will detect it. It is important to note that the ultimate goal of the BPICAS inspection system is to identify the condition of BPI without even needing a ballistic test. The four categories described here indicate the correlation between BPICAS results and the ballistic test results. The commercial inspection system will have only two categories, “Pass” and “Fail”.

3.2. Sample Set 2

A second round of testing was performed on undamaged, recently manufactured BPI. The BPICAS Pass/Fail threshold established using the Sample Set 1 was used to determine the condition of these new BPI. One BPI from this group was tested, damaged using low velocity impact and then retested to observe the changes between the undamaged and damaged condition.

Figure 7 shows the results obtained during this second test. A ballistic test was not performed on this set. However, as they were recently released by the manufacturers, they were expected to pass the ballistic test. Using the BPICAS Pass/Fail threshold determined above, the complete undamaged BPI group was categorized in the region of “True Positives”, in other words “Pass”. The X-Ray results also indicated that these BPI had no indications of damage.

For the damaged BPI, the BPICAS detected an almost twenty-fold increase in the BPICAS value from undamaged to damaged condition. Visual evaluation of this BPI indicated considerable damage. The BPICAS Pass/Fail threshold categorizes this BPI into “True Negatives” region, in other words “Fail”. In the figure, ballistic performance of this BPI was called “Fail” here even though a ballistic test was not performed.

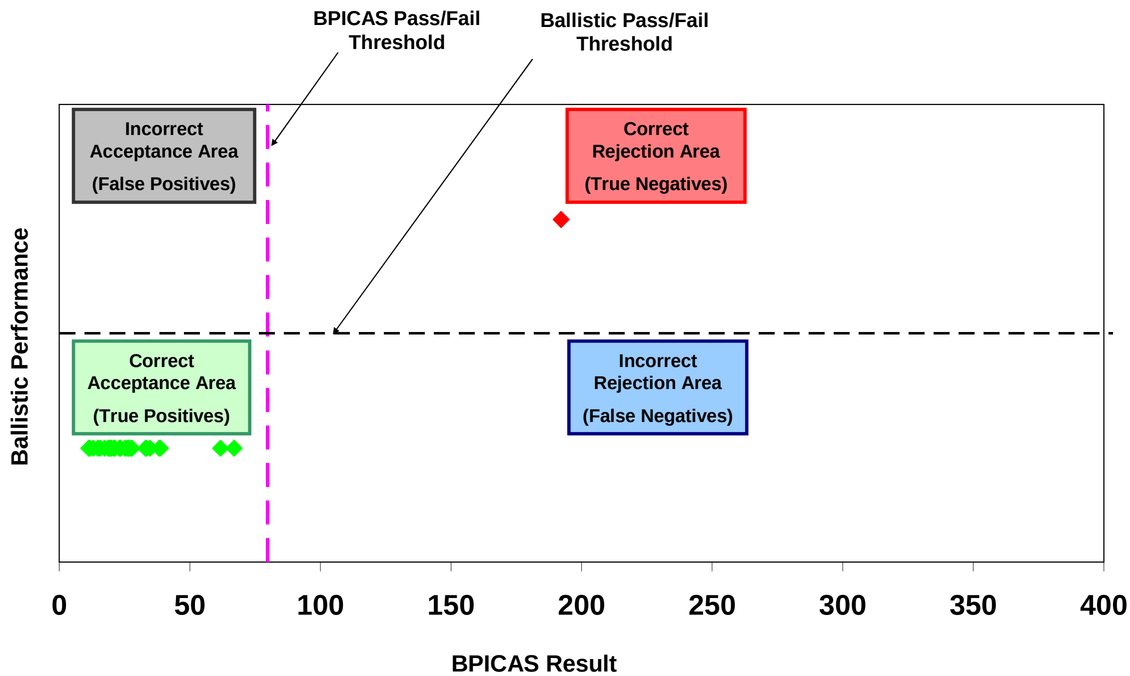

Fig. 7 BPICAS results of the recently manufactured BPI set and the ballistic performance using the distribution areas formed above.

4. DISCUSSION

Currently, the BPICAS requires one minute to inspect a single plate and approximately another minute to determine its condition. The evaluation process can be reduced to 10-20 seconds using a new multimedia parallel processing on the computer CPU. Additionally, the overall inspection time can be reduced by optimizing the sensor design to allow less pressure on the pneumatic cylinders which helps increase the speed of the conveyor belt. A combination of these two approaches can reduce the inspection and evaluation time combined to less than one minute per BPI. Finally, data corresponding to each BPI tested can be easily archived and retrieved for comparison by implementing a bar code reader in the system. This requires that BPI be fitted with a bar code at the manufacturers.

5. SUMMARY

The BPICAS is designed to perform a go/no go type of inspection. This involves Pass/Fail criterion without giving any information about the damage level or location in a sample.

In this study, the BPICAS inspection system was evaluated using two sets of BPI. The first was also evaluated with a digital X-Ray system and ballistic tests. The correlation graph between ballistic test results and the BPICAS results was divided into four categories: “True Positives”, “False Positives”, “True Negatives” and “False Negatives”. The BPICAS Pass/Fail threshold was set at such a level that there would not be any sample grouped in the area of “False Positives”. This threshold was tested on a second set of recently manufactured BPI. The comparison of X-Ray results and the BPICAS results indicated that the BPICAS inspection and the Pass/Fail threshold can nondestructively reveal the damage condition of BPI.

It is expected that additional rounds of testing, which must include a combination of undamaged, controlled-damaged, and fielded BPI, are necessary to establish a statistically sound Pass/Fail criterion for the system before it can be deployed in the field.